The Stellar Halo in the Large Magellanic Cloud: Mass, Luminosity, and Microlensing Predictions

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ABSTRACT

Recently obtained kinematic data has shown that the Large Magellanic Cloud (LMC) possesses an old stellar halo. In order to further characterize the properties of this halo, parametric King models are fit to the surface density of RR Lyrae stars. Using data from both the MACHO and OGLE II microlensing surveys, the model fits yield the center of their distribution at $\alpha = 5^{\mathrm{h}}\ 21.1 \pm 0.8^{\mathrm{m}}$, $\delta = -69^{\circ}\ 45 \pm 6'$ (J2000) and a core radius of 1.42 ± 0.12 kpc. As a check the halo model is compared with RR Lyrae star counts in fields near the LMC's periphery previously surveyed with photographic plates. These data, however, require a cautious interpretation. Several topics regarding the LMC stellar halo are discussed. First, the properties of the halo imply a global mass-to-light ratio of $M/L_V = 5.3 \pm 2.1$ and a total mass of $1.6 \pm 0.6 \times 10^{10} M_{\odot}$ for the LMC in good agreement with estimates based on the rotation curve. Second, although the LMC's disk and halo are kinematically distinct, the shape of the surface density profile of the halo is remarkably similar to that of the young disk. For example, the best-fit exponential scale length for the RR Lyrae stars is 1.47 ± 0.08 kpc, which compares to 1.46 kpc for the LMC's blue light. In the Galaxy, the halo and disk do not resemble each other like this. Finally, a local maximum in the LMC's microlensing optical depth due to halo-on-disk stellar self-lensing is predicted. For the parameters of the stellar halo obtained, this maximum is located near MACHO events LMC-4 and LMC-23, and is large enough to possibly account for these two events, but not for all of the observed microlensing.

Subject headings: galaxies – halos; gravitational lensing – Magellanic Clouds; stars – Population II

1. Introduction

The first strong evidence for the existence of a kinematically hot and metal-poor stellar population in the Large Magellanic Cloud (LMC) has recently been obtained at the European Southern Obervatory's *Very Large Telescope* (Minniti et al. 2003). The radial velocities derived from the spectra of 43 RR Lyrae stars imply a velocity dispersion of 53 ± 10 km s^{-1}, which is larger than that of any other population in the LMC (e.g., Hughes et al. 1991). For comparison, the radial velocities of carbon stars, which represent the bulk population of the LMC disk, have a dispersion of 20.5 ± 0.5 km s^{-1} (van der Marel et al. 2002). Simple equilibrium models of the carbon-star radial velocities suggest that the LMC disk is thick like the Galactic thick disk and flared. Therefore, the LMC is a disk galaxy that has a halo, but not a bulge, and in this regard it is like M33 (van den Bergh 1991).

It is not known how stellar halos form, or how they relate to the other spheroidal components of galaxies (e.g., Wyse & Gilmore 1988). Stellar halos are minor constituents of disk galaxies, and thus they can be difficult to detect. The proximity of the LMC therefore affords a unique opportunity to study an extragalactic stellar halo. How does the LMC's stellar halo compare to the Milky Way's stellar halo? This question illustrates the point that the LMC is a benchmark for understanding galaxy formation and structure, and hence also why measuring the basic parameters of the LMC's stellar halo is important. An accurate model of the LMC's stellar halo also provides a basis for interpreting microlensing results. In fact the stellar halo is a new population unknown in detail to any prior discussion of LMC microlensing, although its possible existence has been considered (e.g., Alcock et al. 2000).

Measurements of the surface density of RR Lyrae stars in the LMC have a venerable history of being used to study the LMC's stellar halo (Kinman et al. 1991). RR Lyrae stars are also used to map the structure of the Galactic stellar halo (e.g., Wetterer & McGraw 1996), and thus their distribution in the LMC can be compared directly to these Galactic data. The starting point for the present work is Fig. 12 of Alcock et al. (2000b) where the radial profile of RR Lyrae star counts in the LMC based on data from 16 MACHO survey fields was presented. There are several reasons why that analysis should be revisited. First, the primary conclusion of Alcock et al. (2000b) regarding the star-count data was the good fit of an exponential disk model; halo models were not thoroughly compared. In addition, new and more accurate catalogs of RR Lyrae stars in 30 MACHO survey fields have since been compiled (inclusive of the 16 noted above), and artificial star tests have now also yielded statistical completeness corrections. Last, a new catalog of RR Lyrae stars from the OGLE II survey is available (Soszyński et al. 2003), and these data can be analyzed together with the MACHO data. The results of this analysis are used to estimate the total mass and mass-to-light ratio of the LMC, and to make predictions about LMC microlensing.

2. Properties of the LMC Spheroid

One way to describe the LMC stellar halo is with King's (1962) model for an isothermal system of particles modified by an external tidal field. The approximate formula for fits to surface brightness data is:

$$S(R) = S_0 \left[\left(1 + (R/a)^2 \right)^{-1/2} - \left(1 + (R_t/a)^2 \right)^{-1/2} \right]^2 \tag{1}$$

where R is the projected radius, and the parameters are the central normalization (S_0), the core radius (a), and the tidal radius (R_t). For $R_t >> a$, Eqn. (1) simplifies to the "Hubble-Reynolds" profile. A good approximation for the density profile of a King model is the "modified Hubble" function:

$$\rho(r) = \rho_0 \left[1 + (r/a)^2 \right]^{-3/2} \tag{2}$$

where r is the spherical radial coordinate. The projection of the modified Hubble function is exactly the Hubble-Reynolds profile, and thus $S_0 = 2\rho_0 a$ for $R_t >> a$. The central density (ρ_0) in mass units is related to the velocity dispersion (σ) by $\rho_0 = 9\sigma^2/4\pi G a^2$ (Rood et al. 1972).

The catalog of RR Lyrae stars used by Alcock et al. (2000b) is known to have serious systematic errors in the number of stars in some fields (e.g., Alcock et al. 2003). The most accurate catalog of RR Lyrae stars in the MACHO database has not yet been published, but was provided by K. Cook (private communication) for the present investigation. Cook's summary[1] refers only to stars that pulsate in the fundamental mode (type RR0 or RRab). These are the easiest to detect due to their large pulsation amplitudes, and they are traditionally used to study the stellar halos. The completeness of the MACHO database is now also better understood because of artificial star tests that were part of the microlensing detection efficiency calculation (Alcock et al. 2001). Unpublished plots of the fraction of artificial stars recovered in the MACHO database as a function of input magnitude were constructed by T. Vandehei (private communication) for 6 example "chunks" of MACHO image data[2]. The completeness fraction of interest has been read off of Vandehei's diagram at $V = 19.4$ mag, which represents a typical LMC RR Lyrae star. As expected, the fraction of recovered V=19.4 stars (f) is correlated with the density of detected objects in each example sub-field (Alcock et al. 2001). The result of a linear fit is $f = 1.37 \cdot \mathrm{N}/\mathrm{N}' = 1.0 - 0.00073 \cdot O$, where

[1] Data available by request to the author.

[2] In fact the results of these tests are not reflected in the luminosity functions published by Alcock et al. (2001), but the results of that work are not affected by the omission.

O is detected objects per arcmin^2 (Alcock et al. 2001, see their Table 2), N is the number of RR0 stars, and N′ is the estimated total number of all types of RR Lyrae stars. This approximate correction has an uncertainty of 7% based on the standard deviation of the fit to the artificial data.

A new catalog of LMC RR Lyrae stars has also recently been published by the OGLE II survey (Soszyński et al. 2003). This catalog includes RR Lyrae stars in all pulsation modes, not just the RR0 stars. Soszyński et al. (2003) suggest that the completeness of their catalog is 95%, but this is not consistent with the calibration obtained below as a free parameter in the profile fit. In order to incorporate these data, the type RR0 stars from OGLE II fields 3–9 are binned into 55 equal-area (96.8 arcmin^2) regions that blanket the central bar.

I adopt a ratio of 1.37 for the total number of RR Lyrae stars to the number of RR0 stars in stellar halos from Kinman et al. (1991). This factor is included in the completeness correction formula above. Note, however, that the Soszyński et al. (2003) catalog implies a ratio of 1.30 for the LMC. The estimate by Kinman et al. (1991) is preferred because it is based on Galactic data, which may be more accurate. In particular, the lowest-amplitude RR Lyrae stars are mostly not of type RR0, and thus it is possible that relatively fewer of these have been detected in the LMC, which would tend to lower the LMC ratio. In any case, the main conclusions of this work are not significantly affected by this assumption.

The King-model fits are performed on the MACHO and OGLE II surface brightness data (V_0 mag/arcsec^2) presented in Fig. 1. It is assumed that every RR Lyrae star represents a luminosity of 6730 $L_{V,\odot}$ in halo stars (Kinman et al. 1991). I adopt a standard distance modulus of 18.5 mag (50.1 kpc), and a tidal radius of R_t = 15 kpc (van der Marel et al. 2002). The adopted value of R_t does not significantly affect the derived parameters (see §2.1). In all there are 85 nearly independent measurements and 5 parameters to fit. The free parameters are the center of the halo, α and δ (J2000), a and S_0 from Eqn. (1), and the fractional incompleteness of the OGLE II data. Inspection of Fig. 1 shows that the majority of MACHO and OGLE II data points are on different lines-of-sight, and are thus independent. The analysis is simplified by assuming that all of the points are independent. An additional 7% error associated with the completeness corrections is added in quadrature with the $\sqrt{N}$ errors, and these are the error bars shown in the main panel of Fig. 1. The best fit has χ^2/dof = 1.19 (dof=79) and parameters: $\alpha = 5^{\rm h}\ 21.1 \pm 0.8^{\rm m}$, $\delta = -69^\circ\ 45 \pm 6'$, $a = 1.42 \pm 0.12$ kpc, and $S_0 = 23.13 \pm 0.07$ mag/arcsec^2. This model is the solid line. The χ^2/dof obtained lends strong support to the accuracy of the derived and adopted parameters. Note that the definition S_0 in Eqn. 1 is not the same as the maximum central surface brightness of the halo, which reaches only 23.35 mag/arcsec^2. The "incompleteness parameter" used in the fit is a way to scale the OGLE II data to best match the profile of the completeness-corrected

MACHO data, and on this basis the OGLE II data employed are only about 80% complete. Finally, inspection of a map of the fit residuals (not shown) reveals no indication of ellipticity. A main result of this calculation is the estimate of the core radius.

The center of the distribution of RR Lyrae stars agrees well with the infrared and optical centers of the LMC bar: $\alpha = 5^{\rm h}\ 25.0 \pm 0.1^{\rm\ m}$, $\delta = -69^\circ\ 47 \pm 1'$ (van der Marel 2001), and $\alpha = 5^{\rm h}\ 23.6^{\rm\ m}$, $\delta = -69^\circ\ 44'$ (de Vaucouleurs & Freeman 1973), respectively. For comparison, Soszyński et al. (2003) report $\alpha = 5^{\rm h}\ 22.9^{\rm\ m}$, $\delta = -69^\circ\ 39'$ for the center of the RR Lyrae distribution in the OGLE II catalog. Overall, these estimates suggest that the LMC center is known to an accuracy of about $10'$. Note that the RR Lyrae center is grossly inconsistent the kinematic center of the H I gas, but it is consistent with the kinematic center of the carbon stars (van der Marel et al. 2002).

2.1. Tidal Radius

Before microlensing surveys existed, surface density measurements of LMC RR Lyrae stars were made by blinking photographic plate images. These data, although obtained by primitive methods, provide a direct test of the accuracy of the halo model derived above. In addition, the fields surveyed with photographic plates are located farther from the center of the LMC than the now available microlensing survey data, and thus they should be useful to constrain the tidal radius, and to test if the halo is spherical at these radii. Of course the situation might not be so simple. For example, the possible existence of extra-tidal stars near the LMC's periphery could complicate the interpretation of the tidal radius.

The photographic RR0 star-count data summarized by Kinman et al. (1991) are reproduced in Table 1, which lists the field name (associated with a globular cluster in each field), the radial distance from LMC center, the area surveyed, and the observed number of RR0 stars. The numbers of RR0 stars expected according to the spherical halo model are listed for easy comparison. These data are also compared in the inset panel of Fig. 1. Significant discrepancies are obvious. The worst case is the NGC 1783 field where the observed number of RR0 stars is probably only about 50% complete. However, the agreement is fair in the two outermost fields (Reticulum & NGC 1841). Inspection of the images of these fields underlines the fact that they are very empty, and thus confusion is not an issue, and that the RR0 stars are detected with reasonably high signal-to-noise. Therefore, the photographic data should be interpreted with caution, but perhaps not dismissed entirely. Finally, however, an attempt to fit Eqn. (1) to these photographic data yields no better constraint on the tidal radius than the current best kinematic estimate of 15 ± 4.5 kpc (van der Marel et al. 2002).

3. Implications for the Dark Halo

The new model of the LMC stellar halo yields information about the total mass of the LMC complementary to what is already known from the rotation curve. The most accurate estimate of the maximum circular velocity of the LMC disk is based on carbon stars (van der Marel et al. 2002): $V_C = 65 \pm 16$ km s^{-1} at the last measured radius of 8.9 kpc. Extrapolating out to the tidal radius implies a total mass of $1.47 \pm 0.85 \times 10^{10} M_\odot$. The estimated total V-band luminosity of the LMC is $3.0 \times 10^9 L_V$ in Solar units, and hence the global mass-to-light ratio is $M/L_V = 4.9 \pm 2.8$ (van der Marel et al. 2002; see also Alves & Nelson 2000).

If the stars in the core of the LMC's stellar halo have a Maxwellian velocity distribution, then the expected velocity dispersion is $\sigma = V_C/\sqrt{2} = 46 \pm 11$ km s^{-1}. This is in good agreement with $\sigma = 53 \pm 10$ km s^{-1} measured by Minniti et al. (2003). Adopting the measured estimates of σ and a, King's core-fitting method yields a central mass density $\rho_0 = 2.3 \pm 1.0 \times 10^8\, M_\odot$ kpc^{-3}. The assumptions of King's method are that mass follows light, that the orbits of the RR Lyrae stars are isotropic, and that the LMC is in equilibrium. The central surface brightness of the LMC is 20.56 mag/arcsec^2 (Bothun & Thompson 1988), which therefore implies $M/L_V = 5.3 \pm 2.1$ for $S_0 = 2\rho_0 a$. For the total V-band luminosity given above, the predicted total mass of the LMC is $1.6 \pm 0.6 \times 10^{10} M_\odot$. The error bars on the estimated mass-to-light ratio and total mass are dominated by the uncertainty of σ.

4. The Stellar Halo Resembles the Disk

Instead of a spherical halo model, an exponential disk model fit to the data in §2 yields a radial scale length of $\lambda = 1.47 \pm 0.08$ kpc, a maximum central surface brightness of 23.15 ± 0.07 mag/arcsec^2, and $\chi^2/\mathrm{dof} = 1.19$ (dof=82). This model is the dotted line in Fig. 1, and it is statistically indistinguishable from the best-fit halo model. (The center and incompleteness of the OGLE II data are fixed to the values found above, but the results are the same if this assumption is relaxed.) An exponential is known to usually provide a good fit to the core of an isothermal, as found here.

Although the LMC's halo and disk are kinematically different, the shape of the surface density profile of the RR Lyrae stars is remarkably similar to that of the young disk. For example, the best-fit exponential scale length for the RR Lyrae stars is very close to the scale length of the LMC's blue light: 1.46 kpc (Bothun & Thompson 1988). For comparison, the Milky Way's stellar halo as traced by RR Lyrae stars does not look like an exponential disk; it has a power-law density profile $\rho(r) \propto r^{-3.024}$ (Wetterer & McGraw 1996) from 0.6 to 80 kpc, which projects to a surface density profile that is obviously different from exponential

models that best represent the Milky Way's disk.

5. Implications for Microlensing

The basic parameters of the LMC's stellar halo were unknown to any prior discussion of LMC microlensing (e.g., Salati et al. 1999; Gyuk et al. 2000). The following approximate calculation is the first to use a modified Hubble density model. The optical depth for a thin inclined disk embedded in a distribution of lenses is given by (Gould 1993; Guidice, Mollerach & Roulet 1994):

$$\tau = \int_0^{D_{OS}} \frac{4\pi G\rho(r)}{c^2}\ell\left(1-\frac{\ell}{D_{OS}}\right)d\ell \;\approx\; \frac{4\pi G\rho_\circ a^3}{c^2}\int_0^{\ell_{max}} \frac{\ell\, d\ell}{\left[\ell^2+k_1\ell+k_2\right]^{3/2}} \tag{3}$$

where r is the spherical radial coordinate, $\rho(r)$ is the density of lenses, D_{OS} is the distance between the observer and source stars, ℓ is the line of sight, and the density $\rho(r)$ is from Eqn. (2). The approximation is to drop the term ℓ/D_{OS} because the LMC's tidal radius is a factor of a few smaller than the LMC's distance. The constants in the denominator are: $k_1 = -2b\cos\phi\tan i$ and $k_2 = b^2\cos^2\phi\tan^2 i + a^2 + b^2$, where ϕ is position angle relative to the far minor axis of the disk, the impact parameter is b, and the disk has an inclination angle i. The integration limit is $\ell_{max} = b\cos\phi\tan i + (R_t^2 - b^2)^{1/2}$. Dwight (1961) solves the integral (see Eqn. 380.013), and thus:

$$\tau \approx \frac{4\pi G\rho_\circ a^3}{c^2}\left[\frac{(R_t^2-b^2)^{1/2}}{(R_t^2+a^2)^{1/2}}\frac{(b\ \cos\ \phi\ \tan\ i)}{(a^2+b^2)} + \frac{(\ a^2+b^2+b^2\cos^2\phi\ \tan^2 i\ )^{1/2}}{(a^2+b^2)} - \frac{1}{(R_t^2+a^2)^{1/2}}\right] \tag{4}$$

The first term in Eqn. (4) is an odd power of $\cos\phi$, which yields the highest values on the far side of the inclined disk.

The LMC disk is generally known to contain interstellar dust, and this opacity will tend to suppress the rate of disk-on-halo lensing relative to halo-on-disk lensing. Therefore, the existence of the LMC stellar halo implies a new local maximum in the LMC optical depth map whose location depends in part on the parameters of the halo as given by Eqn. (4). A ratio of $M/L_V = 1.6$ is typical of stellar halos (Kinman et al. 1991), and this implies $\rho_0 = 6.3\times10^6\,M_\odot$ kpc^{-3} for the LMC stellar halo following §2. Adopting a disk inclination of 34.7° and a line-of-nodes at position angle ∼130° measured East of North (van der Marel et al. 2002), Eqn. (4) predicts a maximum of $\tau = 9\times10^{-9}$ at a distance of 0.95 degrees from center at position angle ∼220°. This is nearest to microlensing events 4, 5, 22, and 23 from Alcock et al. (2000; their Table 8). Excluding event 5, which is caused by a lens

in the Galaxy, and event 22, which is a peculiar supernova, events 4 and 23 account for an optical depth of 1.2×10^{-8}. Therefore, based on location and approximate contribution to the observed optical depth, it is possible that MACHO events LMC-4 and LMC-23 are halo-on-disk stellar self-lensing. The remaining events in the MACHO sample (excluding 5, 22, and the self-lensing event LMC-14; Alcock et al. 2001b) account for an optical depth of 8.2×10^{-8}, which is not explained by stellar lenses in the LMC or Galaxy.

6. Conclusion

A King model fit to RR Lyrae star-count data in the LMC yields the center of their distribution at $\alpha = 5^{\rm h}\ 21.1 \pm 0.8^{\rm m}$, $\delta = -69^\circ\ 45 \pm 6'$ (J2000) and a core radius of 1.42 ± 0.12 kpc. As a check, the predicted numbers of halo RR Lyrae stars near the LMC periphery are compared with counts based on photographic plates. However, these data require a cautious interpretation. King's core-fitting method implies a mass-to-light ratio $M/L_V = 5.3 \pm 2.1$ and total LMC mass $1.6 \pm 0.6 \times 10^{10} M_\odot$. It is noted that the shape of the surface density profile of the LMC's halo is very similar to that of its young disk, which is not the case for the Galactic disk and halo system. Finally, the stellar halo is predicted to cause a local maximum of microlensing optical depth large enough to possibly explain MACHO events LMC-4 and LMC-23, but not all of the observed events. Further observations of RR Lyrae stars that might test the spherical LMC halo model include more surface-density data near the tidal radius, more kinematic data, and accurate distances on multiple lines of sight.

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Table 1. RR Lyraes from Photographic Surveys

Field	log R	A	N_O	N_P
NGC 1783	0.63	1.3	61	144
NGC 2210	0.65	0.64	40	64
NGC 1466	0.91	0.6	3	10
NGC 2257	0.93	0.6	15	8
Reticulum	1.08	0.6	1	1.5
NGC 1841	1.16	0.6	2	0.2

Note. — This table refers only to type RR0 (=RRab) stars. N_O is observed number from Kinman et al. (1991); A is surveyed area in deg.^{2}; R is radius from center in deg.; N_P is the number predicted by the halo model (see text).

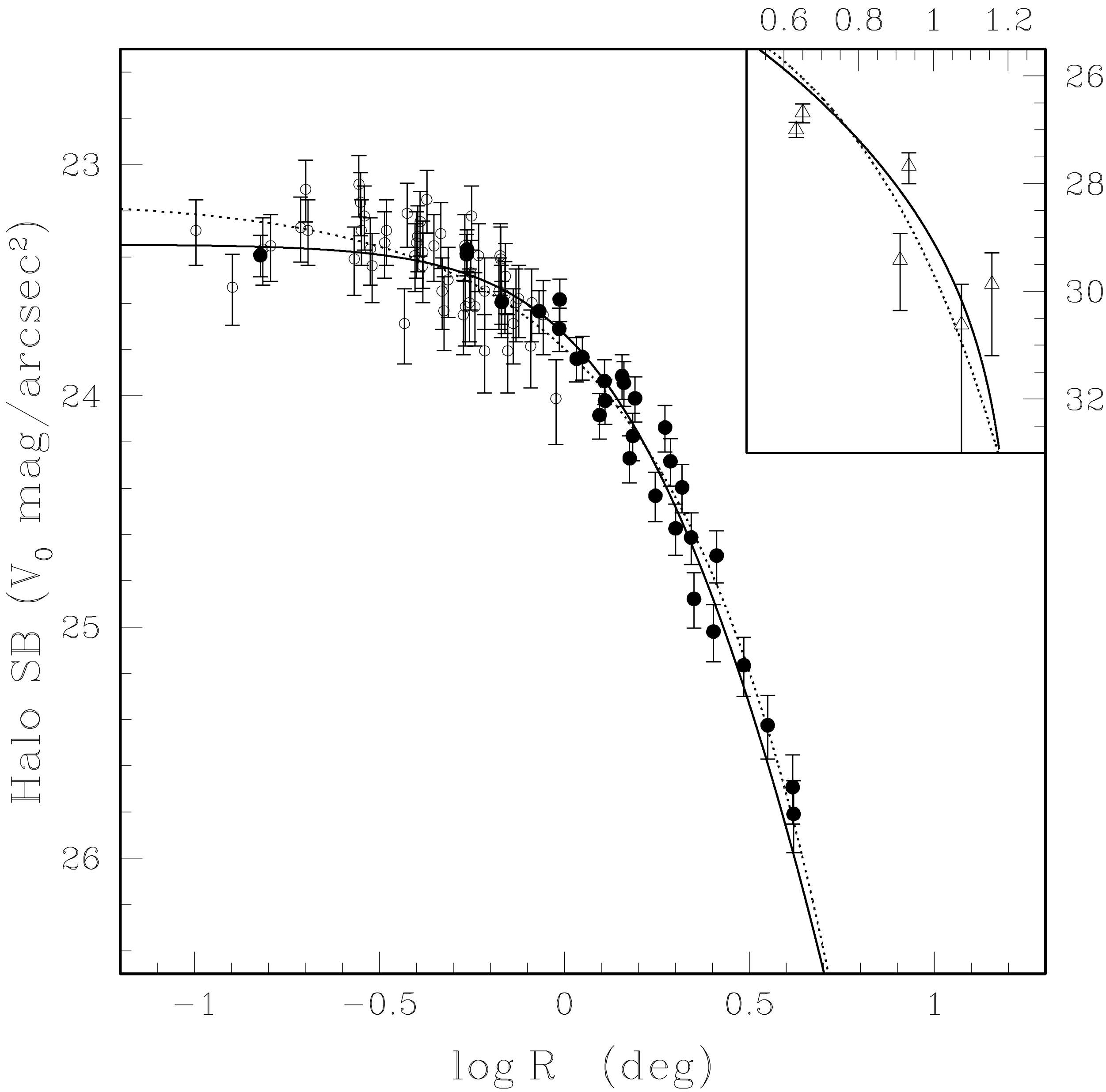

Fig. 1.— Surface brightness of the LMC stellar halo calculated from RR Lyrae star counts. In the main panel, the error bars are $\sqrt{N}$ plus a 7% contribution associated with the statistical completeness corrections. The solid line is the best-fit halo model, and the dashed line is the best-fit exponential disk model. The inset panel shows photographic data (Table 1) for fields at large radial distance; these error bars are $\sqrt{N}$.